DOE Automotive Fuel Cell Development Program

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Background

Fuel cells represent a developing technology which could potentially replace the internal combustion engine in all areas of the transportation sector. They operate with significantly higher fuel efficiency, greatly reduced emissions, and are capable of running on a variety of fuels (such as hydrogen, ethanol, methanol, and natural gas). The widespread introduction and use of fuel cell vehicles could have a major impact on reducing petroleum consumption and on improving air quality in urban areas. This paper provides an update on the status of the U.S. Department of Energy (DOE) program directed at the development of fuel cell propulsion systems for transportation applications.

The Department of Energy recognized the potential of fuel cells for transportation applications and began development of a phosphoric acid fuel cell (PAFC) powered bus in 1987. The transit bus platform was chosen because it offered the most flexibility in packaging the fuel cell and auxiliary component technology available at that time. By 1990, the proton-exchange-membrane (PEM) fuel cell had demonstrated sufficient progress in performance, and a light-duty fuel cell vehicle program was launched with General Motors. Methanol was selected as the fuel because of its availability, simplicity of storage, rapid refueling, high energy density, and ability to be easily reformed. Serious consideration has also been given to other fuel options: in 1994, DOE initiated programs with two industry teams led by Ford and Pentastar (a Chrysler subsidiary) to develop direct hydrogen-fueled PEM fuel cell propulsion systems. In 1995, a contract was awarded to Arthur D. Little, Inc. to develop a flexible-fuel processor capable of reforming gasoline, ethanol and other common transportation fuels. Throughout its short history, the DOE program has continued to support exploratory research on critical components and materials to address technological barriers to commercialization.

Program Drivers. This program is responsive to requirements of the U.S. Energy Policy Act of 1992 (EPACT) which authorizes the development of fuel cell vehicles. This program also represents the key fuel cell work being done under the Partnership for a New Generation of Vehicles (PNGV) -- a U.S. government/industry research and development initiative involving representatives from seven Federal agencies and the Big Three automakers (Chrysler, Ford, General Motors). DOE's program specifically addresses the PNGV goal of developing a vehicle to achieve up to three times the fuel efficiency of today's comparable vehicle. There is keen international competition in the race to develop PEM power systems for automobiles -- extensive efforts are underway in North America, Europe and Japan.

Introduction

Technology Benefits (Energy, Environment, Economy). The United States consumes more petroleum for transportation alone than is produced domestically and the gap is growing.

Transportation accounts for one-fourth of all U.S. energy consumption and two-thirds of its petroleum use. The transportation sector is also a major source of air pollution; responsible for about half of the pollutants that form smog in our cities. Moreover, these adverse energy and environmental impacts are forecast to worsen; increases in vehicles and the miles traveled per vehicle will probably offset the gains resulting from greater energy efficiency and better emission controls in new vehicles. Fuel cells in transportation can be a key technology to combat these adverse energy, environmental and economic impacts:

- *Fuel cells can dramatically lower energy use. The operating efficiency of fuel cell propulsion systems is approximately double that of current internal combustion engine systems. (Fundamental laws of thermodynamics limit the maximum efficiency of turbines and internal combustion engines. As electrochemical devices, fuel cells have an inherently higher maximum theoretical efficiency.)*

- *Fuel cells can dramatically lower air pollution. The emissions of regulated pollutants from a fuel cell vehicle using methanol would be about 100 times below current and proposed national standards. In addition, increased efficiency can decrease the emission of greenhouse gases, which are not regulated but have an adverse effect on the climate.*

- *Fuel cells can increase use of alternative fuels. Fuel cells are capable of running on hydrogen or fuels from which hydrogen is detached such as ethanol, methanol, and natural gas. Decreasing the amount of imported petroleum could ease the trade deficit and increase national security.*

- *Fuel cell vehicles in widespread use would enhance U.S. leadership in fuel cell development and* *manufacturing and also create a new growth industry along with jobs for a stronger U.S. economy.*

Discussion

PROGRAM GOAL - The goal of the DOE Fuel Cells in Transportation Program is to develop highly efficient, low or zero emission automotive fuel cell propulsion systems. Specific objectives include: By the year 2000, validate fuel cell propulsion systems that are (a) 2-3 times more energy efficient than today's comparable vehicles; (b) more than 100 times cleaner than Federal EPA Tier II emissions standards; and © capable of operating on hydrogen, methanol, ethanol, natural gas, and gasoline. In addition, by the year 2004, our objective is to validate fuel cell propulsion systems that meet customer expectations in terms of cost (competitive with conventional vehicles) and performance (equivalent range, safety, and reliability as conventional vehicles).

PROGRAM CHALLENGES - In order for fuel cell propulsion systems to reach their potential, significant technical challenges must be met, including: size and weight reduction, rapid start-up and transient response capability, fuel processing development, manufacturing cost reduction, complete fuel cell system integration, and durability and reliability demonstration. Non-technical barriers to fuel cell vehicle commercialization such as the lack of an alternative fuel infrastructure are also critical.

PROGRAM STRATEGY - The program strategy is to work with all stakeholders by means of a National Fuel Cell Alliance. This government/industry alliance includes domestic automakers, component suppliers, fuel cell developers, national laboratories, universities, and the fuels industry. Currently, under the alliance, each of the three domestic automakers are pursuing different technical approaches by means of cost-shared research projects with DOE. Additionally, pre-competitive fuel cell R&D managed by DOE will attempt to resolve fundamental problems and issues associated with fuel cells and ancillary components that apply to a number of different fuel cell propulsion systems. Each automaker team will have access to the technology and products resulting from the pre-competitive R&D. The Fuel Cell Alliance approach has significant benefits for both DOE and America's automakers. By sharing the results of pre-competitive R&D, government and industry will be able to leverage research dollars. By maintaining their own independent vehicle integration team, the automakers will be able to pursue the approaches which they believe provide the greatest payoffs.

In a recent planning workshop, industry and laboratory experts reviewed the program and developed a recommended list of the R&D priorities and a preliminary fuel strategy for fuel cells in transportation. Fuel processing, fuel cell stack components (such as membranes, catalysts, and bipolar plates), and system components (such as heat exchangers, compressor/expanders) are areas where focussed R&D is needed. As current system development contracts with automakers end in 1997, a different program approach will be in place. DOE will contract directly with fuel cell suppliers and component developers, thus allowing all automakers access to the improvements being made among the suppliers.

Current Status

Table 1 is a listing of prime contractors, project description and project duration under the current DOE program.

TABLE 1: CURRENT DOE PROGRAM CONTRACTS

CONTRACT	OBJECTIVE	LENGTH (MONTHS)
General Motors	Methanol fueled, fully integrated PEM system	30
Ford	Hydrogen-fueled PEM system *Full performance approach*	39
Chrysler	Hydrogen-fueled PEM system *Design-to-cost approach*	36
A.D. Little	Multi-Fuel Fuel Processor	12
Nat. Labs: BNL, LANL, LBNL, ANL	Exploratory Fuel Cell Component R&D	On-going
International Fuel Cells	Direct Methanol Fuel Cell (DMFC) Stack	12
Energy Partners	Novel PEM Stack	18
Texas A&M Univ.	Novel PEM Stack	12
A.D. Little	Scroll Compressor/Expander	15
Vairex	Variable Piston Comp/Expander	15
Allied Signal	Turbo Compressor/Expander	15

FUEL CELL PROPULSION SYSTEM DEVELOPMENT
General Motors (GM) completed a three-year effort in 1993 which demonstrated proof-of-feasibility for methanol-fueled, proton-exchange-membrane (PEM) fuel cells in automotive applications. The GM program is currently in Phase II, which will result in the demonstration of a 30-kW system. Advancements are being made in three key areas: In the fuel processing area, the design of a 50-kW reformer is complete; a new reformer catalyst with twice the activity of the best previously known reforming catalyst has been identified and a fast starting fuel vaporizer has been developed. In the fuel cell stack area, GM demonstrated

500 hours of single cell operation of coated titanium bipolar plates (which are lighter and less costly than machined graphite plates); developed a coating process for metallic bipolar plates; and fabricated and tested electrodes with ultra-low platinum loadings, critical in cost reduction. In the system integration area, GM has developed low cost hydrogen and flow sensors; and stand-alone operation of the 10-kW PEM fuel cell system was achieved using a Powerex air compressor-expander, and real-world automotive components such as fluid injectors and pressure regulators. The General Motors development team includes the General Motors R&D Center as prime contractor and several participating divisions of Delphi Automotive Systems. Key subcontractors include DuPont and Ballard Power Systems.

Ford's Phase I competition among five fuel cell developers is completed. The developers were International Fuel Cells, Energy Partners, H Power Corporation, Mechanical Technologies, and Tecogen. The task was to deliver a 10-kW PEM stack for a direct hydrogen system with a performance goal of 3.7 kg/kW within the one-year time frame. Two of the developers will continue in Phase II with the design, fabrication and testing of a 50-kW fuel cell system. A preliminary conceptual vehicle design and an extensive hydrogen infrastructure and vehicle safety analysis have been completed. Directed Technologies, Air Products & Chemicals, Praxair Inc., Electrolyser Corporation, and BOC Gases performed the hydrogen-related issues analyses. A new state-of-the-art hydrogen storage tank liner was developed by Lawrence Livermore National Laboratory, EDO Fiber Sciences and Aero Tec Labs. This technology greatly reduces the fuel storage size which is critical in the vehicle design.

Chrysler/Pentastar's fuel cell work, being done by Allied Signal, is focussed on a design-to-cost approach in which materials development plays a critical role. Low-cost bipolar plates and low-cost membranes have been developed. Work is progressing with fabrication of 10-kW stack hardware and durability testing of low-cost bipolar plate materials. Performance problems encountered with the scale-up of the low-cost fuel cell design are being resolved. Scale-up to a 30-kW system is planned by January of 1997. Pentastar is supported by Chrysler Liberty, Allied Signal Aerospace, Allied Signal Automotive, and Allied Signal Research and Technology.

FUEL PROCESSING AND STORAGE R&D

DOE awarded a contract to Arthur D. Little, Inc in 1992 to develop fuel processor systems for reforming methanol, ethanol, natural gas, and other hydrocarbons for use in transportation fuel cell systems, and for development of advanced systems for hydrogen storage on vehicles. This project is intended to provide fuel flexibility for fuel cell powered vehicles, and to reduce fuel processor size and cost, reduce start-up time, and increase transient response capability. Steam reforming, partial oxidation, and combinations of these processes were investigated. In FY 1994, a 25-kW reformer and a 1-kg hydrogen storage proof-of-concept systems were built and tested. In FY 1995, a 40-kW partial oxidation (POX) ethanol fuel processor was built and tested; the State of Illinois co-sponsored this effort. In FY 1996, the development effort will culminate in a petroleum-based fuel processor. The main technical challenge is in reducing the carbon monoxide level in the fuel stream, which is a poison to the fuel cell system.

COMPONENT R&D

Exploratory research at Los Alamos National Laboratory, Lawrence Berkeley National Laboratory and Brookhaven National Laboratory is focussing on advanced fuel cell concepts such as direct methanol oxidation in low-temperature fuel cells (DMFCs), improved materials and components for PEM, and electrocatalyst research. Two key objectives are reducing catalyst poisoning and methanol crossover. Research at Argonne National Laboratory has resulted in a quick-start, lightweight, compact methanol partial oxidation reformer that will be inexpensive to manufacture. In addition to reformer R&D, Argonne is characterizing alloy catalysts for CO tolerance and electrochemical methanol oxidation, developing a dynamic fuel processor and system model, characterizing novel cathode materials for direct methanol solid oxide fuel cells (SOFC), and modifying a battery test facility to include fuel cell testing capability.

In 1996, six new cost-shared contracts were awarded under a program research and development announcement for novel fuel cell stack development (International Fuel Cells, Texas A&M, Energy Partners) and compressor/expander development (Allied Signal, A.D. Little, Vairex). International Fuel Cells will be developing a conceptual design of a direct methanol fuel cell stack focussing on methanol impermeable membranes and advanced anode catalysts. Texas A&M

University will be developing a small-scale PEM stack addressing low platinum and platinum alloys, advanced membranes, internal humidification concepts, lightweight composite materials, and water/thermal management. Energy Partners will be developing a small-scale PEM stack focussing on bipolar plate flow optimization, cell stack design studies, and low platinum loading membrane-electrode assembly techniques. A.D. Little, Allied Signal, and Vairex will be developing three different prototype compressor/expanders (scroll, turbo, and variable piston, respectively) designed specifically for automotive fuel cell systems.

New Initiatives

The plan for August 1996 is to release a new solicitation for innovative research and development of (1) a complete, integrated fuel cell power system consisting of an advanced fuel-flexible fuel processor that reforms common transportation fuels (e.g., methanol, ethanol, gasoline, and natural gas) and an advanced 50-kW PEM fuel cell stack, and (2) any material, component, or process that will address a single critical issue in developing fuel cell technology for transportation applications.

Conclusion

The future for fuel cell technology looks very promising. Fuel cells have the potential to revolutionize the way in which power is generated for all types of vehicles. With successful development, fuel cells could have the equivalent technological impact on society in the first half of the 21st century as the internal combustion engine did in the first half of the 20th century.

Department of Energy Automotive Fuel Cell Development Program

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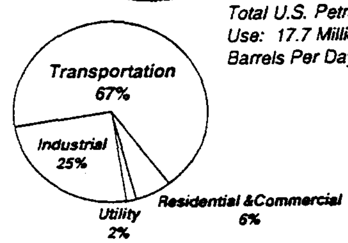
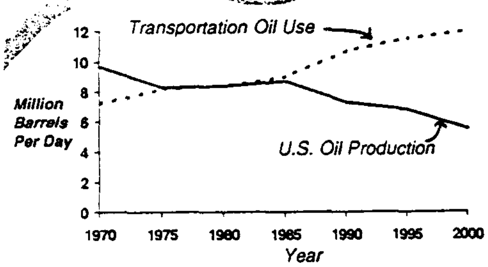
Customer Coordination Meeting, October 28, 1996

1995 U.S. Petroleum Usage: Transportation Sector is Key Contributor

Total U.S. Petroleum Use: 17.7 Million Barrels Per Day



U.S. Has Growing Dependence on Imported Oil



Technology Benefits

Fuel Cell Vehicles in widespread use can ....

- Dramatically lower energy use
  - >double efficiency of the ICE engine
- Dramatically lower air pollution
  - Zero or near-zero emissions
- Increase use of alternative fuels
  - Multi-fuel reforming is fuel flexible
- Reduce dependency on foreign oil
- Create jobs & industry

GOALS AND OBJECTIVES

GOAL:

- DEVELOP HIGHLY EFFICIENT, LOW OR ZERO EMISSION AUTOMOTIVE FUEL CELL PROPULSION SYSTEMS UTILIZING CONVENTIONAL AND ALTERNATIVE FUELS

GOALS AND OBJECTIVES

OBJECTIVES:

BY 2000, VALIDATE FUEL CELL POWER SYSTEMS THAT ARE:

- >51% ENERGY EFFICIENT AT 40 kW MAX POWER
- >100 TIMES CLEANER THAN EPA TIER II EMISSIONS
- CAPABLE OF OPERATING ON CONVENTIONAL AND ALTERNATIVE FUELS

BY 2004 VALIDATE FUEL CELL POWER SYSTEMS THAT MEET CONSUMER EXPECTATIONS IN TERMS OF:

- COST COMPETITIVE TO INTERNAL COMBUSTION ENGINES
- EQUIVALENT PERFORMANCE, RANGE, SAFETY AND RELIABILITY

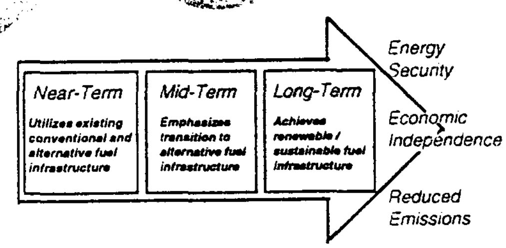
Program Technical Challenges

- Start-up & Transient Response
- Fuel Processing Development
- CO Clean-up / Tolerance
- Size & Weight Reduction
- System Integration
- Reliability & Durability Demonstration
- Manufacturing Cost Reduction

Program Strategy

- ***National Fuel Cell Alliance:*** *Domestic automakers, fuel cell developers, component suppliers, national labs, universities, fuels industry*
- ***Barrier focussed system and component R&D:***
  (1) Fuel Cell Stack (membranes, catalysts, bi-polar plates)
  (2) Fuel Processing (multi-fuel reforming, CO clean-up)
  (3) System Components (compressors, heat exchangers, sensors & controls)

Fuel Strategy



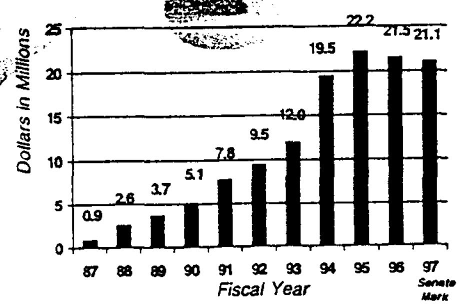
Major Projects

CONTRACT	OBJECTIVE	LENGTH
GM	Methanol-fueled, fully integrated PEM system	2.5 years
Ford	Hydrogen-fueled PEM system based on full performance approach	3.25 years
Chrysler	Hydrogen-fueled PEM system based on design-to-cost approach	3.0 years
A.D. Little	Multi-Fuel, Fuel Processor Development	1.0 year
LANL, ANL, LBNL, BNL	Exploratory Fuel Cell Component R&D	On-going

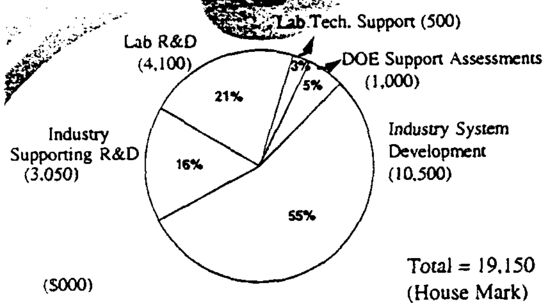
Major Projects (continued)

CONTRACT	OBJECTIVE	LENGTH
International Fuel Cells	Direct Methanol Fuel Cell (DMFC) Stack	12 months
Energy Partners	Novel PEM Stack	18 months
Texas A&M University	Novel PEM Stack	12 months
A.D. Little	Scroll Compressor/Expander	15 months
Vairex	Variable Piston Compressor/Expander	15 months
Allied Signal	Turbo Compressor/Expander	15 months

Program Funding History



FY'97 DOE Funding Allocation by Participants



GM Project

Team: GM R&D, Delphi Energy & Engine, Delphi Harrison, Delphi Packard, Delco Electronics, DuPont, Ballard

FY'96 Accomplishments

- Designed and assembled 30kW catalytic combustor and integrated into methanol reformer (0.5 kW/l)
- Two 30 kW Ballard stacks built (0.3 kW/l)
- A 3.5 mil Nafion membrane developed by DuPont with improved performance and handling characteristics

FY'97 Planned Accomplishments

- Fabricate and complete testing of 30 kW fuel processor system (reformer, shift, PROX)
- Complete integration and testing of 30 kW (net) PEM fuel cell power system (brassboard) with fuel processor and completed 50 kW stacks

Ford Project

Team: Ford, IFC, MTI, DTI

FY'96 Accomplishments

- Prepared Preliminary Conceptual Vehicle Design Report and Hydrogen Vehicle Safety Report
- Fabricated prototype hydrogen storage tanks
- Tested 10kW stacks from suppliers and initiated scale-up phase to 50kW

FY'97 Planned Accomplishments

- Complete Conceptual Vehicle Design Report for battery augmented fuel cell vehicle
- Develop two 50 kW stack systems (0.25 mg/cm^2 Pt, and 0.35 kW/kg)
- Test direct hydrogen stack systems under automotive drive cycles

Chrysler/Pentastar Project

Team: Pentastar, Chrysler Liberty and AlliedSignal Aerospace, Automotive and R&T Divisions

FY'96 Accomplishments

- Developed Prototype II baseline design of 0.62 kW/l at 0.7 mA/cm^2 @0.5 V
- Identified new cannister/packaging material to improve power density by 15% and developed new molded support plate material to improve power density by 20%
- Developed carbon-coated metal and titanium nitrided bipolar plates

FY'97 Planned Accomplishments

- Resolve bowing and corrosion of carbon-coated bipolar plates and continue parallel efforts in conductive plastic bipolar plates
- Validate Prototype II design: 5 cell, 30 cell, 10 kW with improvements (flowfield, mspg, cannister) and test under auto drive cycle loads

FY97 New Systems Projects

FY'97 Plans are to make 1-2 awards for 2-3 year projects for an automotive fuel cell power system

- 50 kW PEM fuel cell stack system integrated with 50 kW fuel flexible fuel processor
- Technology capable of operating on gasoline, ethanol, methanol, and natural gas
- Project goals will be established using Year 2000 technical targets

Sub-System & Component R&D

FY'96 Accomplishments

- Completed testing of 50 kW ethanol POX reformer (85% conversion and 1% CO output) - A.D. Little
- Developed and initiated testing of fuel flexible 40 kW fuel processor for gasoline (0.7 kW/l, 0.6 kW/kg) - A.D. Little
- Held design reviews for high efficiency, lubrication-free compressors/expanders - A.D. Little, Vairex, and Allied Signal
- Initiated advanced PEM stack development for optimized flow fields, improved MEAs and bipolar plates - Energy Partners
- Initiated advanced PEM stack development for ultra-low Pt electrodes, advanced membranes, internal humidified MEA, low cost bipolar and end plates - Texas A&M
- Initiated development of advanced membrane and catalysts for direct methanol fuel cell - IFC

Sub-System & Component R&D

FY'97 Planned Accomplishments

- Complete testing of integrated 40 kW fuel flexible fuel processor with gasoline, include LANL PROX sytstem and controls (<10 ppm CO). Integrate with fuel cell. - A.D. Little
- Complete investigation for alternative CO clean-up catalysts- A.D. Little
- Deliver three 50 kW compressor/expander systems with off-shelf motor/controller (68%, 4l, 3kg)- A.D.L., Vairex, AlliedSignal
- Complete MEA downselect and cell testing, design advanced 1-2 kW stack (projected to 0.8 kW/l and 0.8 kW/kg)- Energy Partners
- Verify performance in 1 kW stack (projected to 0.8 kW/l and 0.8 kW/kg) and design automotive PEM concept - Texas A&M
- Evaluate MEAs in single cell test and design 5 kW DMFC- IFC

Sub-System & Component R&D
New Procurement

FY'97 Plans are to make multiple awards for 1-3 year projects (depending on scope) to address critical fuel cell and fuel processing R&D priorities

- Lightweight, low-cost bipolar plates
- Fuel processing CO clean-up and fuel cell CO tolerance
- Improved transient response for fuel processing systems
- Reduced size and cost of 'balance of plant' components (heat exchangers, etc.)
- Improve manufacturability of components and materials

Laboratory R&D: **Los Alamos National Lab**

FY'96 Accomplishments

Direct Methanol

- Reduced methanol cross-over from 120 to 30 mA/cm^2
- Demonstrate cathode catalyst loading lower than 1 mg/cm^2

Reformate-Air

- Demonstrated stable cell performance for 300+ hours with 100 ppm CO (1000 hr goal)
- Demonstrated novel humidification concept (using composite backing layer)
- Designed and developed PROX system for integration with ADL fuel flexible fuel processor

Laboratory R&D: **Los Alamos National Lab**

FY'97 Planned Accomplishments

Direct Methanol

- Demonstrate 1000 hrs stable operation at T>100°C with 1*M* MeOH feed
- Verify operation above 100°C with 80% fuel utilization and 0.15 W/cm^2
- Demonstrate 100mA/cm^2 @0.5V with < 1mg/cm^2 anode catalyst

Reformate-Air

- Demonstrate CO tolerance at 1% CO level by anode PA-PBI cells
- Define cathode and cell operation conditions to achieve 0.2 W/cm^2 with PB-PBI cell operating on H_2 + 1% CO
- Demonstrate novel humidification concept in short stack
- Demonstrate molded, mechanically viable carbon/plastic bipolar plate/flowfield (0.01 ohm cm^2)

Laboratory R&D: **Argonne National Lab**

FY'96 Accomplishments

- Developed quick-starting, low temperature, catalytic methanol POX reformer (50% H_2 and 0.8% CO w/o shifter, 0.4% with)
- Completed technology transfer of catalytic methanol POX reformer to industry
- Evaluated reforming catalysts for low-temperature, POX reforming of hydrocarbon fuels (achieved >40% at <500°C)
- Completed characterization of alloy anode catalysts for CO tolerance and electrochemical methanol oxidation
- Developed dynamic (transient) model for steam reformers
- Completed characterization of novel cathode materials for ceramic direct methanol fuel cells
- Initiated modification of battery test facility to provide fuel cell testing capability

Laboratory R&D: **Argonne National Lab**

FY'97 Planned Accomplishments

- Optimize catalysts/conditions for low-temperature POX reforming of hydrocarbon fuels
- Develop dynamic (transient) model for POX of hydrocarbon fuels
- Develop complete fuel cell system transient models to support PNGV systems analysis activities
- Evaluate potential CO getters and oxidizing agents to identify promising materials for CO clean-up
- Complete modification of battery test facility to provide fuel cell testing capability

Laboratory R&D: **Other National Labs**

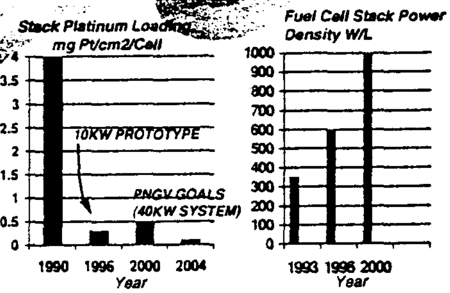
FY'96 Accomplishments

- Developed new technique (NMR) for electrode evaluation- LBNL
- Discovered that the alloy Pt,Re has the lowest potential for CO oxidation ever reported- LBNL
- Developed new theory of oxygen reduction on small Pt particles- LBNL
- Utilized x-ray absorption to increase understanding of catalyst activity and kinetics-BNL

FY'97 Planned Accomplishments

- Develop CO tolerant catalysts using new NMR tool- LBNL
- Synthesize and test ternary alloy catalysts-BNL
- Develop compact steam generator using microchannel technology- PNNL

Rapid Progress is Being Made in Achieving Technical Targets



Conclusion

- *Fuel cells have the potential to revolutionize the automotive industry.*
- *Fuel cells in transportation can provide a more energy efficient use of our resources and a cleaner environment.*
- *The DOE program is addressing critical research and development areas, thus removing barriers to a transportation fuel cell market*